ATTACHMENT H

PACK ICE INTERACTION WITH STAMUKHI SHOAL, BEAUFORT SEA, ALASKA

by

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I. INTRODUCTION

The morphology of the Beaufort sea continental shelf is characterized by a series of linear shoals occurring slightly landward of the 20-m depth contour. These shoals interfere with the shifting ice pack and localize the formation of grounded ice ridges and hummocks, which in turn serve as "strong points" in the establishment of the seasonal ice zonation. Despite the scouring action of drifting ice, the crests of the shoals are not worn down, indicating rapid reconstruction by unknown processes. Shoreward migration of several shoals supports this notion (Reimnitz *et al.*, 1978a, b; Reimnitz and Maurer, 1978).

Piles of grounded ice on shoals, called stamukhi, protect the inner shelf from pack ice forces, allow the growth of relatively smooth, immobile fast ice, and thereby indirectly facilitate the development of oil resources. The shoals have more direct value to petroleum development in artificial island construction because, as a rule of thumb, each vertical foot of fill costs 2 to 3 million dollars. Thus, an understanding of processes affecting the stability of the shoals and the mechanisms of ice interaction has considerable importance.

Major ice piles seen repeatedly during the first several years of Landsat coverage in the same area of the Beaufort Sea shelf suggested the presence of a large topographic high where none was charted (Fig. 1). The USGS R/V KARLUK was used in 1977 to survey a 17-km-long linear shoal that rises as much as 10 m above the surrounding seafloor. The shoal, called Stamukhi Shoal, stands out on satellite images obtained in most summers and winters since then. Because Stamukhi Shoal, as a well-defined and dynamic feature, occupies a key position relative to ice zonation, we have extended our studies in recent years to make it the best known shoal on the Alaskan shelf.

In this report we use Landsat images to show the effects of Stamukhi Shoal on winter and summer ice regimes of the last 10 years. We also use side-scan sonar records, fathometer records, and direct diving observations to provide details of seafloor morphology and its changes resulting from ice keel interaction and

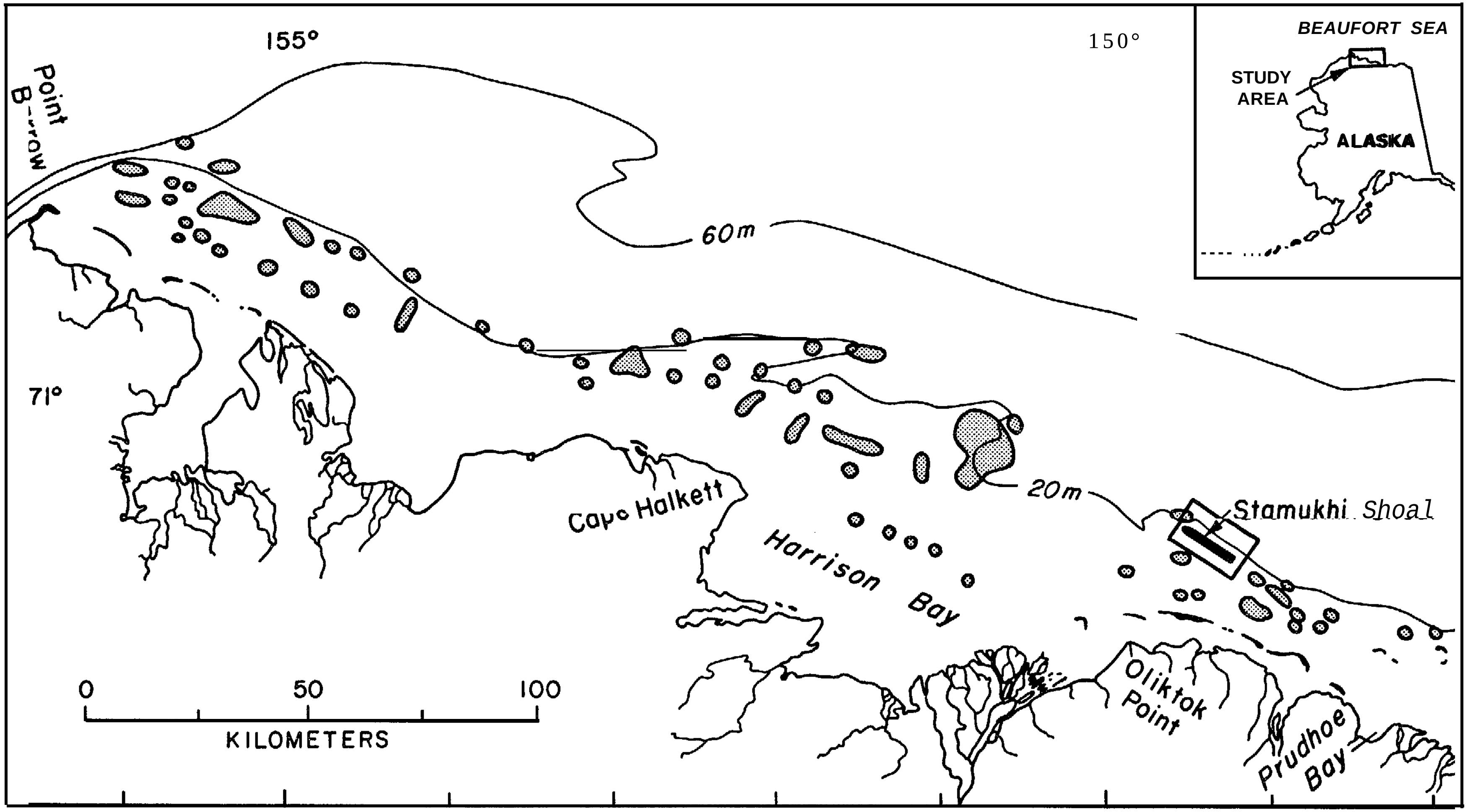


Figure 1. Map of study area showing all isolated shoals covered by less than 6 fm (11 m) of water (stippled areas), as taken from NOS chart no. 16004. Stamukhi Shoal lies where no shoal was charted. The two shoals indicated offshore and inshore of the vest tip of Stamukhi Shoal, along with certain other shoals shown on chart 16004, do not exist where charted, but the indicated belt of bathymetric anomalies is characteristic of the stamukhi zone. The box around Stamukhi shoal delineates Figs. 2, ?, 8, and 10.

currents affecting the shoals. Finally, other shelf surface anomalies along a line east and west of Stamukhi Shoal and forming the seaward boundary of the fast-ice zone will be discussed.

II. BACKGROUND INFORMATION

Soviet investigators and scientists were the first to note the role of shoals in the establishment of yearly ice zonation in the Laptev and Best Siberian Seas. Zubov (1945) reported: "The importance of shallows also is manifested in the fact that ice heapings of various sorts, having considerable vertical measurements, ordinarily become grounded on shallower places like banks, rocks, and shoals. Later, these heapings, under the pressure of the ice from the sea, increase in size, become more durable, and play the role of offshore islands in the development of fast ice."

In recent years increasing numbers of observations and studies on the shelves of northern Alaska have shown the interaction between isolated shoals and pack ice. Reimnitz *et al.* (1972) and Reimnitz and Barnes (1974) observed the shadowing effect of topographically high regions on the seafloor that protect the seafloor from drifting ice keels, and they further noted increased ice concentrations and ice gouging (also called ice scouring; see Barnes *et al.*, this volume) on shoals compared with deeper surrounding terrain. With the advent of repetitive coverage by Landsat-1 satellite imagery, certain continental shelf regions were conspicuous because of the recurrence of ice heapings and the subsequent stability of ice piles, suggesting ice interaction with the seafloor (Stringer, 1974a, b; Stringer and Barrett, 1975a, b; Kovacs, 1976; Toimil and Grantz, 1976; Stringer, 1978; Barry et *al.*, 1979). Using a combination of satellite imagery and seafloor data, Reimnitz *et al.* (1978a, b) first noted the role that shoals play in establishing the annual sea-ice zonation in the Beaufort Sea. The Russian term stamukha (plural stamukhi) refers to large ice heaps that form on shoals along the outer margin of the smooth land-fast ice and commonly remain through much of the following summer. Following that usage, Reimnitz *et al.* (1978b) introduced the term "stamukhi zone" for the belt of major grounded-ice ridge systems seaward of the fast ice.

Large stamukhi act as fences and accumulate smaller ice floes. Thus ice commonly prevents access by the small survey vessels used for most studies in this region. The bathymetry, geology and sediment distribution in the stamukhi zone, which straddles the midshelf within the 18- to 35-m depth range, are therefore only poorly known. The belt of isolated shoals stretching along this zone between Point Barrow and Prudhoe Bay shown in Fig. 1 (from NOS chart no. 16004) only indicates where shoals are concentrated; their precise locations are highly uncertain (Reimnitz and Maurer, 1978). However, an unusual ice-free season in 1977 allowed a detailed survey of the Stamukhi Shoal area. Some of the results and background information on linear shoals inshore of Stamukhi Shoal were presented by Reimnitz and Maurer (1978). They concluded that the shoals are reshaped and moved under the influence of ice and are not relict barrier islands dating from times of lower sea level. Thus for an understanding of the shoals, a comparison with superficially similar features on the eastern seaboard of the United States is not useful (Reimnitz and Maurer, 1978).

For detailed descriptions of the regional setting of sea ice and marine processes, refer to Barnes and Reimnitz (1974), Kovacs and Mellor (1974), Reimnitz and Barnes (1974), and Reimnitz *et al.* (1978b). In general, the shelf is ice-covered most of the year, except for the period from mid-July to the end of September when open water, having variable concentrations of ice, exists. The ice motion on the shelf is predominantly from east to west, parallel to the isobaths. Several times during the last 10 years at the onset of winter, no multiyear ice or stamukhi existed in the Stamukhi Shoal area (see Reimnitz *et al.*, 1978b), but big grounded ice ridges were found there several months later. In these years the ice piles were constructed entirely of thin ice that, until it was deformed, could not touch bottom. The relationship between the shoal and the formation of grounded ice ridges along the shoal crest is unknown.

III. METHODS OF STUDY

Two types of data form the basis for this study: satellite imagery and seafloor and ice observations. The best available Landsat images from 1972 through 1981 were studied for ice features related to the presence of Stamukhi Shoal. The results have been compiled for all years of record to distinguish winter and summer effects. Seafloor data in the Stamukhi Shoal area, gathered from the USGS R/V KARLUK in 1977, 1980, and 1981, include side-scan sonar, fathometer, and high-resolution seismic records. Most of the 1977 coverage had precise range-range electronic positioning control and was run at fast speed using the fathometer and 7-kHz subbottom profiler. Only two 1977 crossings of Stamukhi Shoal were surveyed using a Uniboom system* and side-scan sonar at the slow speed required for this work (Maurer *et al.*, 1978). Two diving traverses supplement the 1977 data. All of the 1980 coverage was run at a boat speed of about 3.5 knots using side-scan sonar, a 7-kHz subbottom profiler, and a Uniboom. In 1980, however, only satellite navigation was available, providing intermittent fixes of only ± 1/2-km accuracy and with larger errors in the intervening dead-reckoning periods. Therefore, these records cannot be matched precisely to

Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

the contour chart of Stamukhi Shoal based on the 1977 survey. The navigation control nevertheless is adequate for locating each shoal crossing in its approximate place along the length of the shoal. Numerous grab samples were collected during the 1980 survey and analyzed for grain-size distribution. In 1981 we made two side-scan sonar mosaics using the EG&G SMS 960 seafloor mapping system and precision navigation, one over the northwest tip and one over the southeast tip of the shoal. During the 1981 field work, we also reran three of the accurately positioned 1977 fathometer lines to record changes in shoal morphology; in addition, we towed divers on a sled along one of these traverses.

IV. RESULTS

A. Bathymetry

Stamukhi Shoal is a 10-m-high ridge oriented northwest-southeast parallel to regional isobaths at a depth of 18-20 m (Fig. 2). Except for two small knolls seaward of the northwest tip, the surrounding shelf is smooth with a gentle seaward slope. The shoal terminates abruptly at both ends, with the highest point being near the northwest end. Ten representative shoal cross sections, labeled A through J in Fig. 2, are shown in Fig. 3. No cross section can be called “typical,” and all have considerable microrelief from ice scouring. Jagged local relief occurs on the seaward toe of the shoal. Profiles I and J were smoothed visually to eliminate false relief resulting from rough seas during the survey.

B. Ice Patterns from Satellite Images

From the first Landsat image of the study area in July 1972 and extending through the winter of 1981, the presence of Stamukhi Shoal is revealed either by characteristic ice types or as a boundary for sea-ice distribution. Winter ice patterns are best exhibited in satellite images taken just prior to sea-ice breakup. At that time, high features, from which meltwater has drained, are white. These high areas contrast sharply with smooth, low-lying ice that collects meltwater and appears dark. Figure 4 is a Landsat image covering extensive regions east and west of Stamukhi Shoal. The crest of the shoal is marked by strong lineations from ice ridging and separates smoother ice on the seaward side from a triangular hummock field reported by Stringer (1974b). The ice landward of the shoal is immobile at this time, held by grounded ridges on the shoal, while some of the adjacent ice is beginning to move. Reimnitz and Barnes (1974) used this image to delineate the outer edge of the fast ice following the crest of Stamukhi Shoal without knowledge of its existence. A lack of multiyear ice on the Beaufort Sea shelf during the previous freeze-up indicated that the grounded ridges on Stamukhi Shoal (Fig. 4) are constructed of thin, first-year

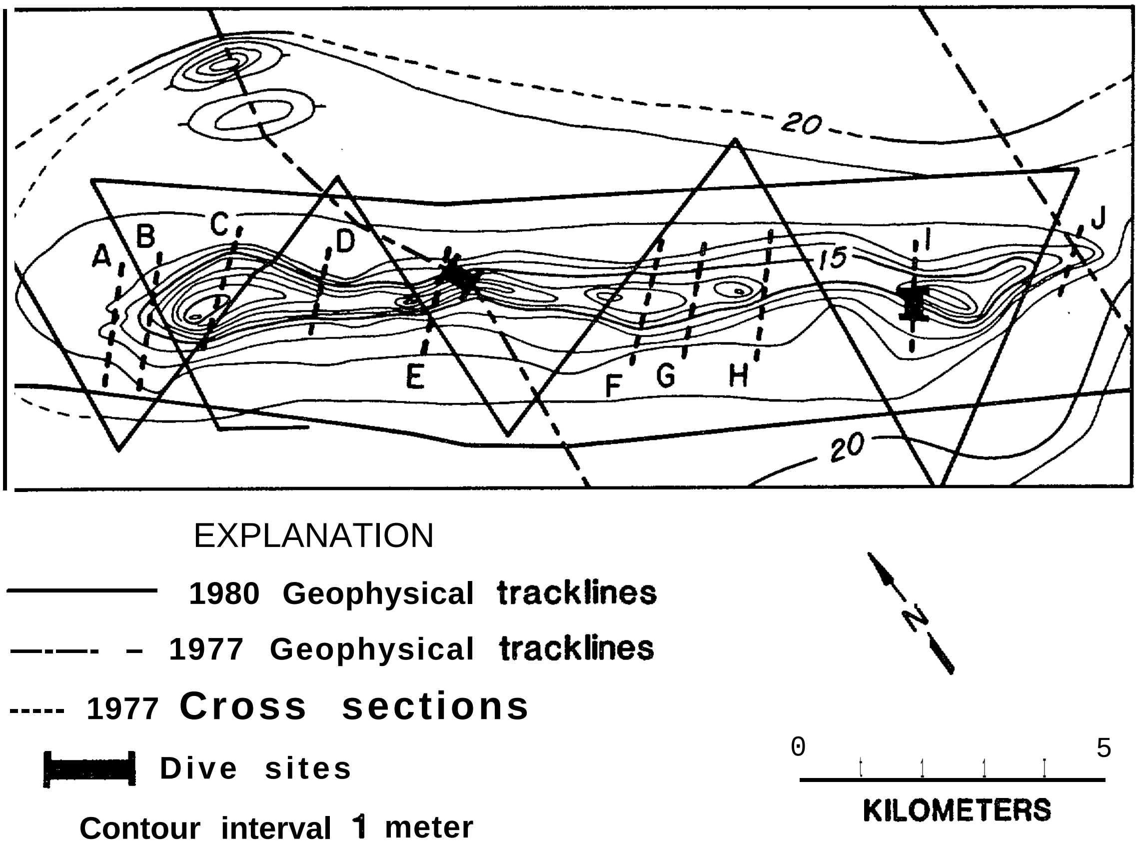


Figure 2. Bathymetric map of Stamukhi Shoal based on 1977 surveys, also showing 1977 and 1980 geophysical tracklines, cross sections A-J of Fig. 3, and two diving traverses. Area covered by this figure is indicated in Fig. 1, and is the same area as Figs. 7, 8, and 10.

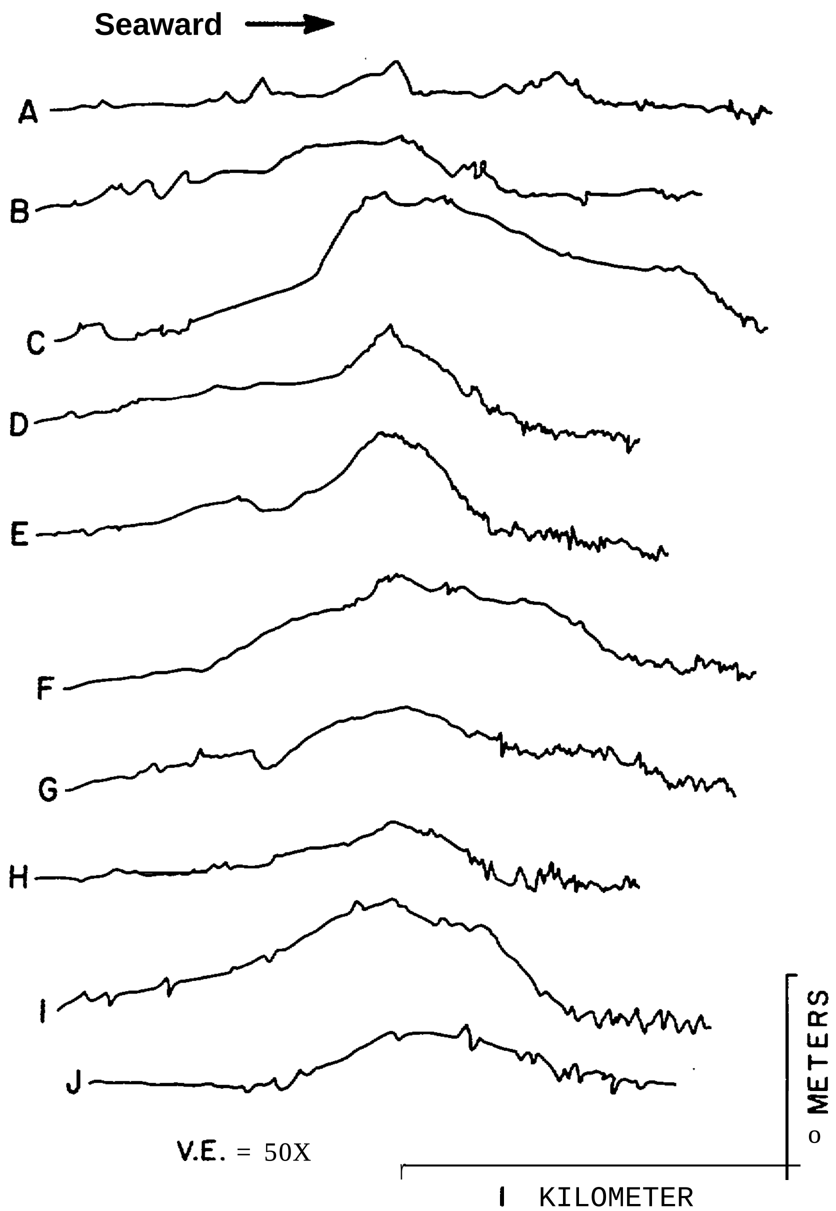


Figure .3. Representative cross sections of Stamukhi Shoal in 1977, including ice-gouged microrelief, locations are shown in Fig. 2.

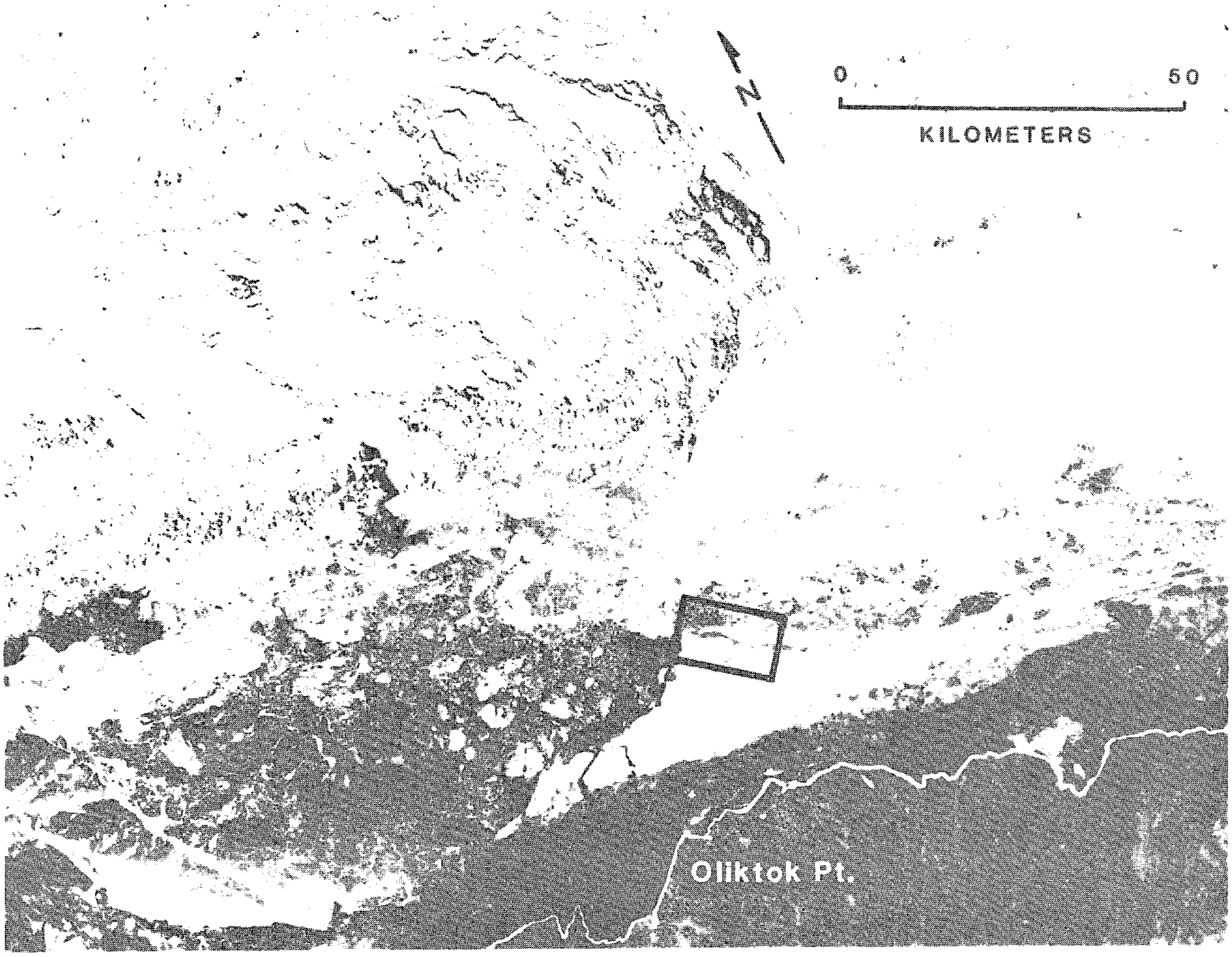


Figure 4 Landsat image of ?/2/73 showing the two most characteristic effects of Stamukhi Shoal on the winter ice regime: (1) The shoal is marked by grounded ridges (E in Fig. 6), and (2) these ridges separate two distinct ice types (F in Fig. 6). The box shows the area of Figs. 2, 7, 8, and 10. For a more detailed analysis of this scene see Reimnitz et al. (1978b).

ice, which in the undeformed state could not touch bottom (Reimnitz *et al.*, 1978b). This lack of multiyear ice during freeze-up and through the winter was repeated for at least two more seasons (1977-78 and 1978-79) during the study period.

Two typical winter ice effects that resulted from Stamukhi Shoal serving as a strong point are shown in Fig. 4: (1) the linear shoal is a focal point for ice ridging, and (2) the shoal is a boundary between two distinct ice fields.

Figure 5 shows the effects of Stamukhi Shoal and other shoals in the region on drifting ice in a recurring summer pattern. These two Landsat images were taken in 1974 and 1977. The strikingly similar pattern develops under dominant northeasterly wind and westerly current, causing ice to drift onto shoals, and suggests that shoal attrition from ice impacts is occurring. The ice lineation that continues east of Stamukhi Shoal, having a slight seaward en-echelon offset, marks a set of poorly charted shoals 3-4 m high (Rearic and Barnes, 1980).

Besides the two winter manifestations of ice dynamics and the summer situation described above, other patterns can be recognized. We grouped ice patterns or types that are related to, or caused by, Stamukhi Shoal into four summer (Fig. 6A,B,C,D) and three winter categories (Fig 6E,F,G). The seasons in which these seven categories are recognized on available Landsat images are listed in Table I with scene identification numbers. A brief discussion of the categories follows.

(A) Stamukhi Shoal and stamukhi act as barriers to drifting sea ice, generally providing shelter to the inner shelf. The situation depicted in this image followed the indistinct pattern G seen slightly earlier that same season.

(B) Stamukhi Shoal crest is marked by line of stamukhi, with relatively open water on either side.

(C) Stamukhi Shoal corresponds to one margin of a lead. The adjacent ice can move either landward or seaward away from stamukhi on the shoal.

(D) Stamukhi Shoal is marked by a chain of grounded ice-island fragments, tabular massive glacial ice derived from the Ward-Hunt ice shelf (Breslau *et al.*, 1971; Skinner, 1971; Brooks, 1973). In 1972, a large drifting ice island broke up in the Beaufort sea and scattered over 400 fragments, commonly having diameters of 40-100 m but ranging up to 3000 m, along the coast of northern Alaska (Kovacs and Mellor, 1974). Brooks (1973) reported more than 40 fragments were aligned along the 18-m isobath over a distance of 32 km in the area of Stamukhi Shoal.

(E) Ice-ridge lineation is coincident with Stamukhi Shoal, as discussed above.

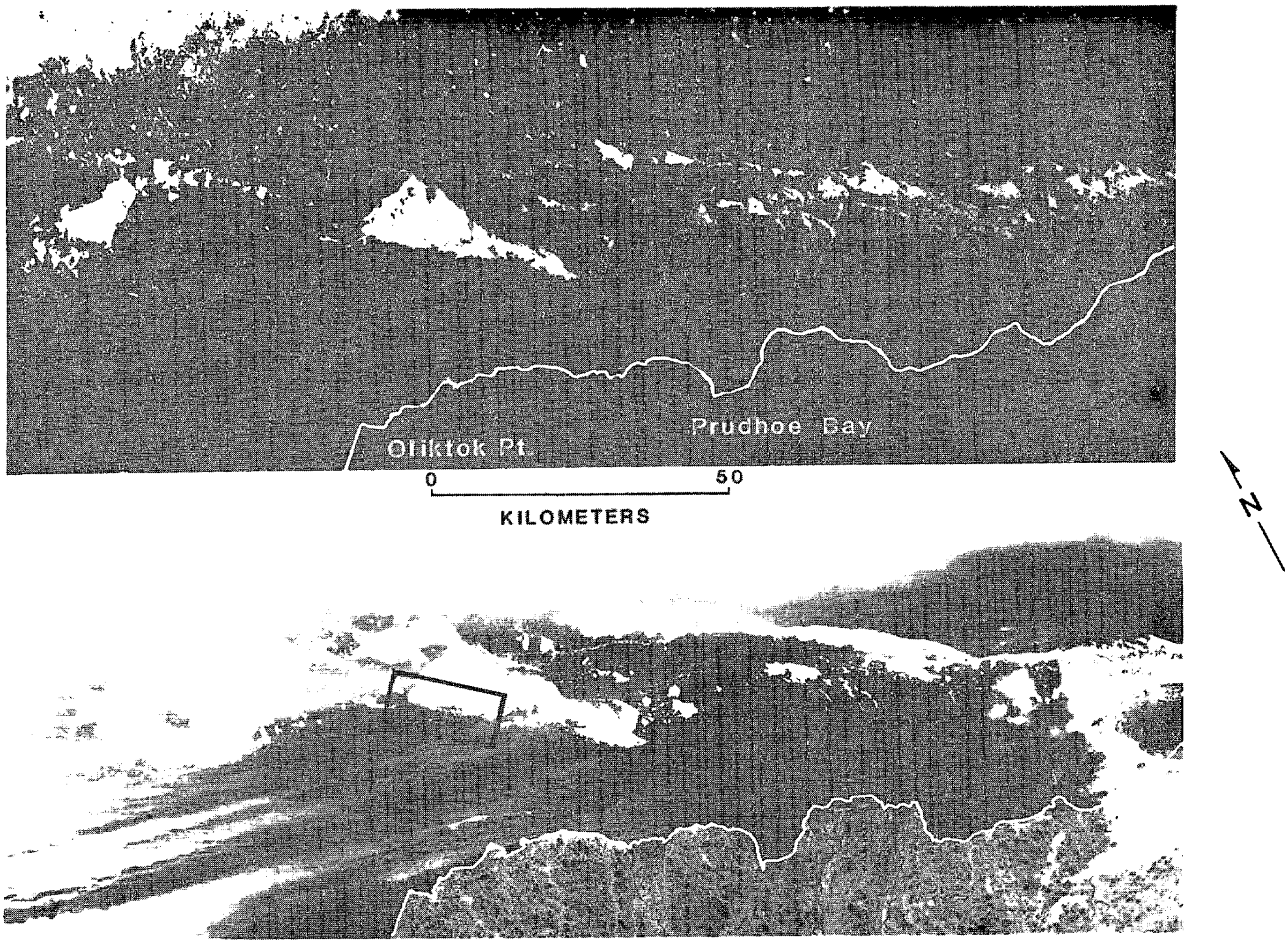


Figure 5. Landsat images of 9/6/74 (top) and 8/12/77, showing a typical recurring summer scene of shoals collecting westward-drifting ice. The crest of Stamukhi Shoal, which obviously suffers a very large number of ice impacts per year, marks the <crier edge of the ice fields north of Oliktok Point. The shore-parallel, en-echelon ice pattern east of Stamukhi Shoal is controlled by a slight break in bottom slope, which is dotted by 3- to 4-m-high shoals (Rearic and Barnes, 1980). The box northeast of Oliktok Point shows the area of Figs. 2, 7, 8, and 10.

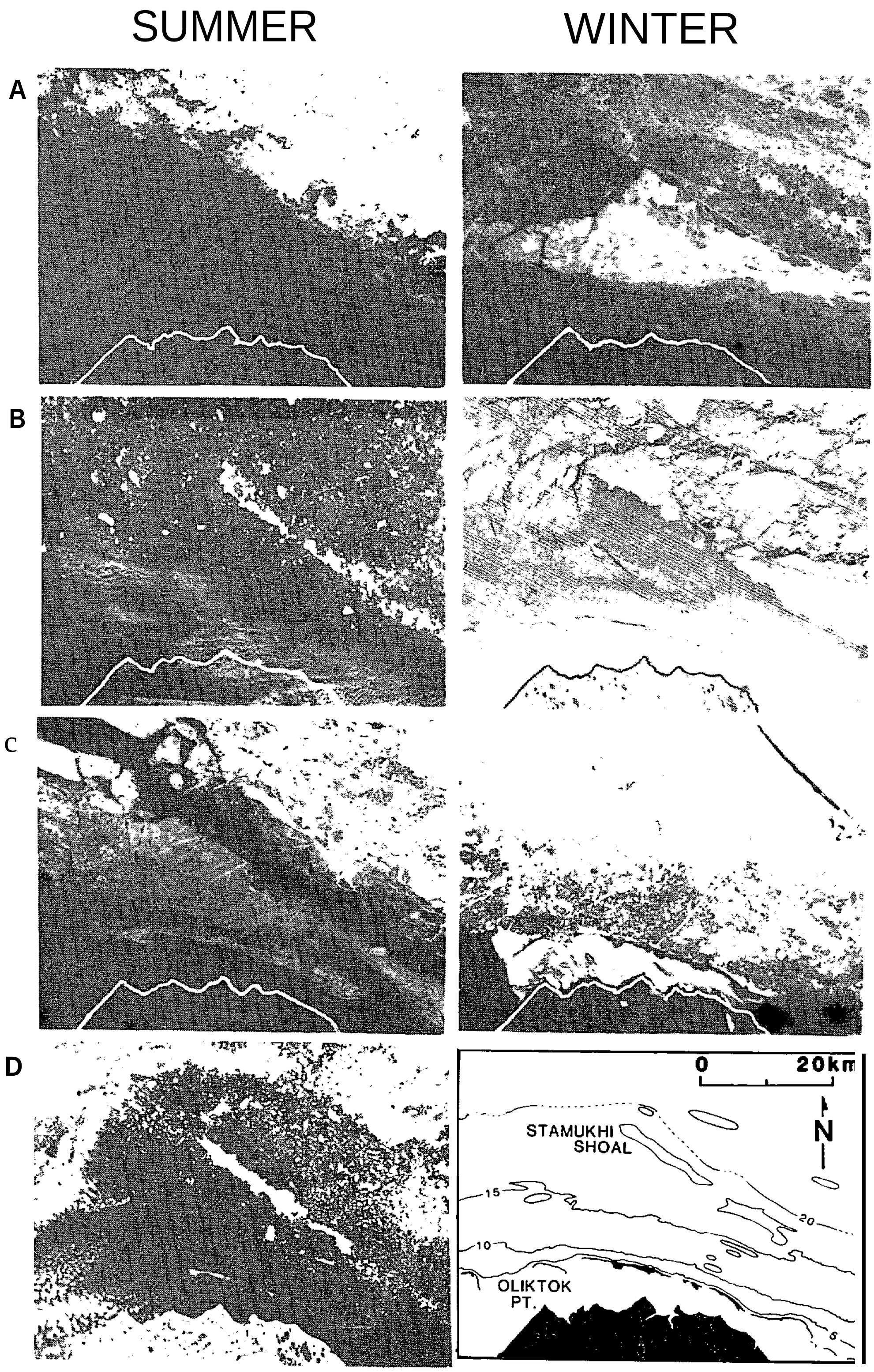


Figure 6. Seven types of summer and winter ice patterns controlled by Stamukhi Shoal, but not necessarily persisting through entire seasons: (A) drift-ice barrier (7/25/??), (B) stamukhi lineation (3/3/78), (C) lead boundary (7/19/75), (D) ice-island lineation (8/12/72), (E) Ice-ridge lineation (7/2/73), (F) ice-type boundary (10/13/74), and (G) indistinct ice piles 7/?/7?). Map at bottom right shows Stamukhi Shoal and other major shoals in a stippled pattern.

(F) Ice boundary coincides with Stamukhi Shoal and separates two distinct ice types, as discussed above.

(G) Large, indistinct ice piles accumulate along general trend of Stamukhi Shoal. In two winters (1978 and 1979) of such poorly defined ice piles, we flew low-level reconnaissance flights along the shoal and landed in several spots, confirming the existence of massive grounded ice piles. In both of these seasons, no multiyear ice existed in the area, and in May 1978 pressure ridges of new ice contained sand, pebbles, and shells, demonstrating interaction of thin first-year ice with the crest of the shoal.

TABLE I. Ice Patterns A Through G (see Fig. 6), Seasons Observed, and Representative Landsat Images Identified by Number

Year	Winter		Summer	
	Type	ID number	Type	ID number
1972		No data	A	1002-21300 D1020-21281
1973	E	1326-21284		No ice anywhere on shelf
	F	1344-21283		1397-21220
1974	F	1723-21260	A	1775-21124
1975	F	1812-21172	B	2233-21213 C2178-21165
1976	F	2538-21095	A	2592-21082 B2556-21092
1977	G	2896-20434	A	2915-20483
1978	G	30095-21281	A	30164-21115 B30182-21121
1979	G	21635-21044		No data
1980	G	21980-21265	A	30866-21021 BRBV Scene - Aug. 23
1981	F	22339-21193	B	22372-21013

The summary of available satellite observations made from 1972 through 1981 (Table I) shows that Stamukhi Shoal interacted with pack ice in all but two summers (1973 and 1979). Stamukhi Shoal probably interacted with the pack during these two summers as well, but during periods undocumented by Landsat images.

C. Bedforms

The bedforms delineated in the Stamukhi Shoal region by geophysical surveys using side-scan sonar and fathometer include (1) ice gouges, (2) ripple fields, (3) sand waves, and (4) jagged outcrops. Figures 7, 8, and 9 present compilations of bedform data from 1980 and 1981 surveys. These compilations would be quite different if they *were* made using the data collected in 1977, as shown later. The 1980 tracklines were not shifted to fit the accurate 1977 bathymetry, and the sinuous shoal crest plotted for reference on Figs. 7, 8, and 10 is a result of position inaccuracies. However, this is of no consequence to the following discussion.

1. Ice Gouges

Visual comparisons of all 1980 segments of side-scan sonar records against counted segments of sonar records allowed us to group ice gouge densities per kilometer of trackline into four classes (Fig. 7): (1) areas with high gouge densities, estimated 100 or more gouges per kilometer of trackline, an example of which is shown on the left in Fig. 8C; (2) areas with medium gouge densities, estimated 30 to 100 km^{-1}, (3) areas with low gouge densities, estimated 10 to 30 km^{-1}, (as in *Fig.* 8B); and (4) areas with very low gouge densities, an occasional scratch on the seafloor, or no gouges at all, as exemplified in Figs. 8A and 8C on the right side.

High gouge densities occur on the seaward flank of Stamukhi Shoal at depths greater than about 17 m (Fig. 7). At the western end of the shoal the boundary of the intensely gouged terrain swings seaward around small topographic highs, one cresting at 15 m (Fig. 2). Downdrift (south and west) of this small rise is a tongue of low gouge counts, or a "shadow," that is the result of the high ground protecting the deeper water behind it from the scouring action of ice. Medium gouge densities are found in flat terrain landward of the shoal. The landward slope of the shoal, its crest, and the tongue extending seaward off the western end are marked by low gouge densities. Large patches, elongated parallel to the shoal crest on the landward side, have very low gouge densities. The dominant trend of gouges is about east to west, oblique to the shoal. The average gouge incision depth in the intensely scoured terrain is 0.3 to 0.5 m.

The detailed bathymetry of the 1981 eastern Stamukhi Shoal is shown on Fig. 9 with ice gouge sets and texture traced from complete side-scan sonar coverage. In tracing ice gouge patterns

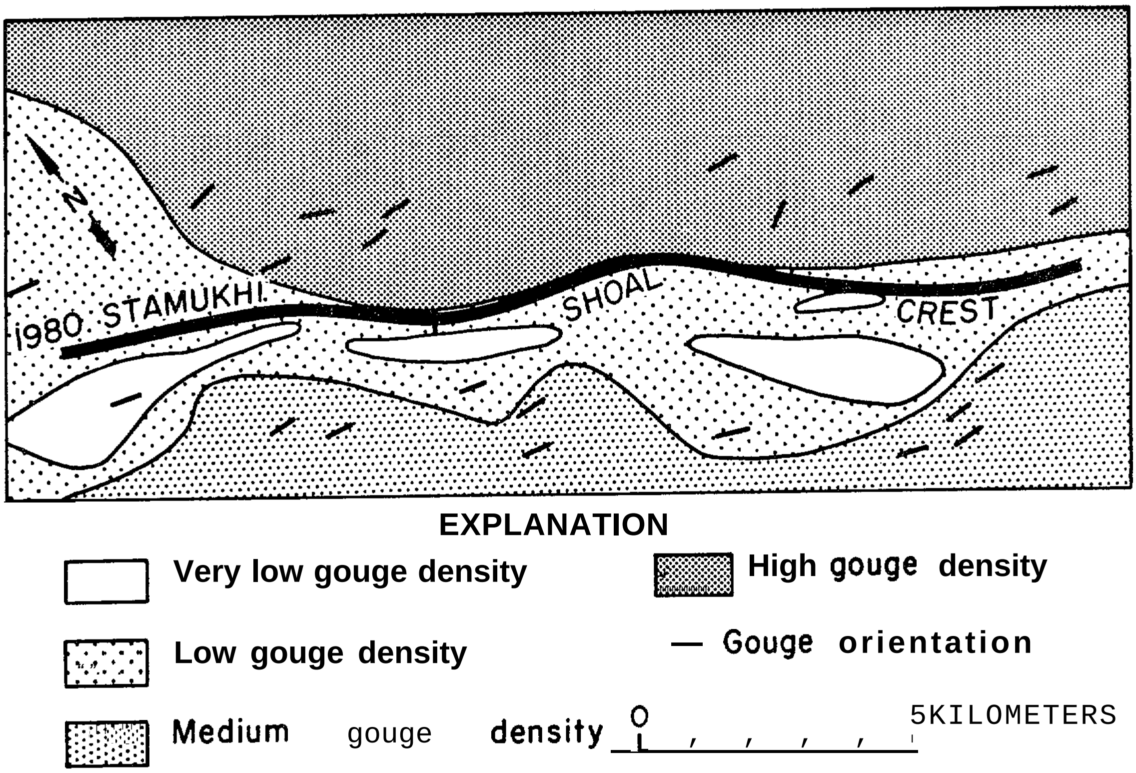


Figure ?. Map of ice-gouge densities and dominant gouge trends on Stamukhi Shoal. The single trend indicator on, and at right angles to, the shoal crest represents only a few gouges and is therefore of little significance. Mapped area matches that of Figs. 2, 8, and 10, and is keyed to Fig. 1.

we have eliminated the striped quality of the digital records by enhancing faint gouges to an average level. The dominant lines in this product represent individual gouges traced, and they show the distance over which each gouge can be followed with certainty. Figure 9 reveals a strong dominant trend of ice gouges from east to west, unreflected by the shoal serving as an obstacle to ice motion. Some individual gouges are over 2 km long, even on relatively steep slopes. For example, a large gouge that cuts east-west across the upper left corner of the mosaic persists through a depth range of at least 3 m. Smaller gouges in the center of the mosaic (for example, below the 18-m contour) rise obliquely across a 1.5-m-high shoal and descend the lee slope. There is no obvious widening of individual gouges with decreasing

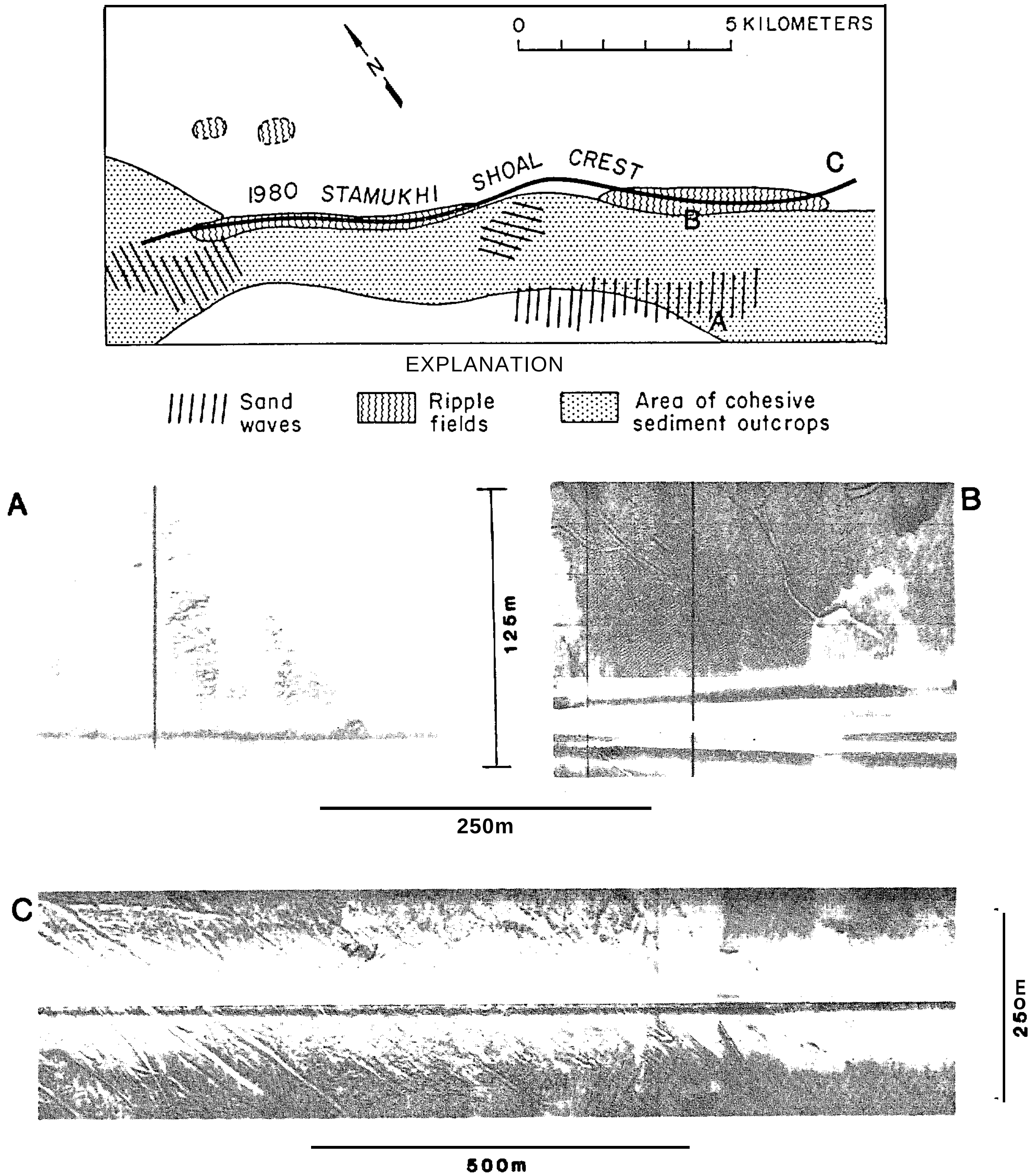


Figure 8. Map showing distribution of bedform types around Stamukhi Shoal in 1980 and 1981 plus sample monographs showing: (A) sand waves that have outcrops of firm cohesive sediments in the troughs and very few gouges on the crests, (B) irregular patch of rippled gravel (dark area) and adjacent, overlapping patches of scrod (light), all only lightly scoured by ice, and (C) swath from seaward area of high-gouge density through pock-marked transition zone into crestal area that has few gouges. Mapped area matches Figs. 2, ?, and 10, and is keyed to Fig. 1.

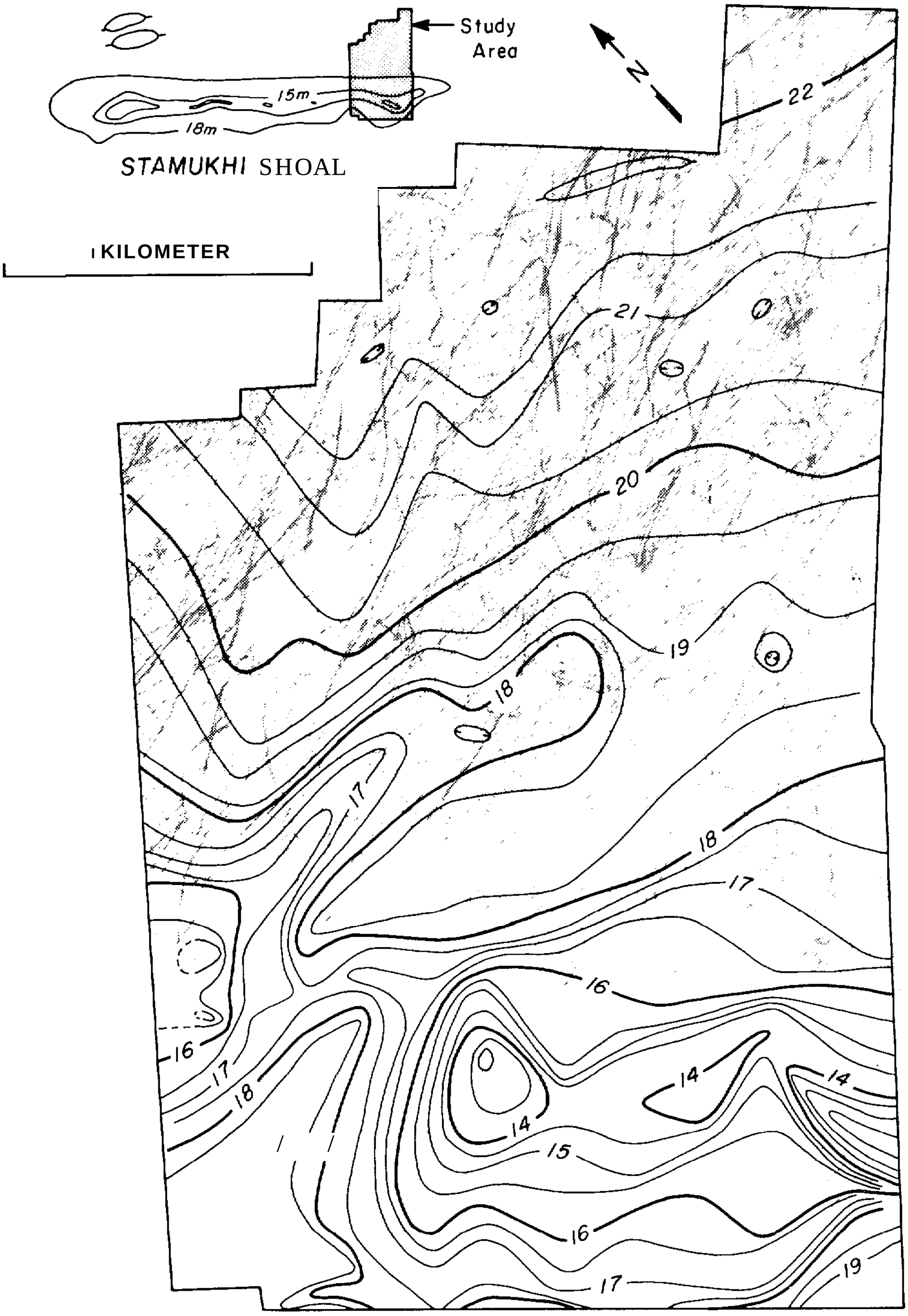


Figure 9. Linedrawing of all ice gouges in an area in the eastern part of Stamukhi Shoal (taken from complete and overlapping side-scan coverage in 1981) superimposed on detailed bathymetry. This demonstrates that individual gouges continue through several meters of relief and that the shoal does not steer the ice.

depth and increasing weight of ice masses ascending the stoss side of Stamukhi Shoal. A rather sharp boundary in the vicinity of the 17-m isobath separates the intensely disrupted seafloor region on the seaward side of the shoal from the only slightly gouged crestal region. The transition from high to low gouge density occurs over a distance of 200 to 300 m (Fig. 8C). In 1981 this transition zone was commonly marked by numerous small, isolated, irregular depressions (center of Fig. 8C), changing upslope into fields of small ripples. Bathymetric details resulting from close line spacing in this mosaic area show that the crest of Stamukhi Shoal is not a long sinuous and continuous feature as depicted in Fig. 2.

2. *Ripple Fields*

Bxtensive fields of rippled bottom were observed along the crest of Stamukhi Shoal in 1980 (Fig. 8, top). Figure 8B shows their slightly sinuous pattern that is cut by several ice gouges. The wavelength of these ripples is 1-1.5 m. The height is estimated at 8-10 cm, below the resolution of the fathometer. The trends of the ripples range from azimuth 130" to 175', but most fall in the narrow range from 150" to 170°. Figure 8B suggests that the ripple field boundary corresponds with a boundary separating coarser sediments from finer (sandy?) sediments outside of the field. The detailed surveys of the eastern Stamukhi Shoal in the 1981 mosaic revealed smaller ripple fields just landward of the heavily gouged terrain. These ripples have the same orientation and spacing as in the previous year, but are absent along the shoal crest. As in the previous year, ripple fields commonly are associated with patchy background textures suggestive of alternating sandy and gravelly deposits.

3. *Sand Waves*

Irregularly spaced sand waves with wavelengths from 50 to over 200 m, heights from 0.5 to 1 m, and crest length from 125 m to more than 250 m, occur in several patches in the lee of Stamukhi Shoal (Fig. 8, top). The surfaces of the sand waves are smooth, while the troughs commonly are marked by jagged relief, described under the section "Outcrops." The trends of the sand-wave crests are uniform within each area, but differ widely between the areas of occurrence (10°, 43°, and 140°, see Fig. 8, top). In the westernmost patch of sand waves, the waves are asymmetrical to the east, suggesting an influence of easterly currents.

4. *Outcrops*

Irregular, jagged outcrops are widely distributed on the lee side of the shoal crest, and they extend seaward of the crest off the northwestern tip (Fig. 8, top). These outcrops appear similar to those occurring over wide regions of the shelf (Reimnitz *et al.*, 1980). The outcrops consist of overconsolidated, cohesive silty clay, which apparently forms under modern processes in arctic shelf regions. Diving observations in numerous areas reveal that the silty clay outcrops range in appearance from highly irregular, jagged outcrops recently disrupted by ice keels to outcrops totally rounded and polished by swift currents. The occurrence of such outcrops in the troughs between hydraulically shaped bodies of granular sediments, as here in the area of sand waves (Fig. 8A), is typical for the inner shelf of the Beaufort Sea.

D. Bottom Sediments

Fourteen surface sediment samples were collected during the 1980 survey on and around Stamukhi Shoal. The locations of the stations and the mud/sand/gravel percentages, determined from textural analyses, are given in Fig. 10. Mud characterizes the low, flat terrain around Stamukhi Shoal, where gouge densities are medium to high (Fig. 7). Coarse granular sediments, that range from clean sand to gravel, make up the body of the shoal, and gravel marks the very crest. As with gouge density, the very northwestern tip of Stamukhi Shoal is different in that sand extends seaward to include the pair of small shoals shown in Fig. 2. Patches of jagged outcrops, representing cohesive deposits on the lee slope of the shoal (Fig. 8, top), indicate that the body of coarse granular material also contains lenses of mud.

The surface samples generally contain numerous clamshell fragments and some very small clams. All samples in the regions of sand and gravel show pronounced iron-oxide staining. Two mud samples seaward of the shoal have a 1- to 2-mm reddish-brown mud layer between firm materials below and a soft ooze layer above. A few pebbles are found even at the sites here labeled as mud, and one of the samples seaward of the shoal included a pebble 5.5 cm in diameter. Pebbles are subrounded to rounded. Areas with gravelly sediments generally are recognized on the monographs by a dark background. This is a result of a multitude of echoes originating from individual clasts. Clean sand on the monographs is characterized by a light-toned and even background (Fig. 8B), commonly separated from gravel by a sharp boundary. Cohesive mud in the regions of high ice-gouge density on the seaward side of the shoal also produces a dark background on monographs and therefore cannot be distinguished from gravel by shades of darkness of the monographs alone. In these regions the dark background is the result of reflections from rough surfaces that were generated by the churning action of ice and preserved in cohesive materials.

E. Diving observations

Direct observations of bedforms, sediments, and organisms, made by scuba diving along two 300- to 400-m traverses in 1977, serve to support survey trackline data and spot samples discussed above. The western traverse is located about 6 km east of the western tip of the shoal, and the eastern traverse is approximately 3 km west of the east tip of the shoal (Fig. 2).

The western diving transect extends from near the crest down the seaward slope of the shoal. Slightly sandy gravel, commonly 2-3 cm in diameter but as large as 6 cm, occurs near the crest. This material, highly disrupted by intense ice action, forms crisscrossing gouges that have 1-1.2 m relief. All recent relief forms are sloping at the angle of repose. Medium-grained sand overlies the gravel in several patches 5-10 m wide. The sand patches are marked by oscillation ripples that have wavelengths of 10 to 15 cm and heights of 3 to 5 cm and are oriented roughly parallel to the shoal. Sparse brown filamentous algae, worm tubes, and a few hydroids are seen in local depressions. The sediments gradually become finer with increasing depth seaward and range from gravelly sand to cohesive mud. Sharp vertical relief forms lacking any signs of bioturbation are seen in this mud.

Along the lee slope of the shoal on the eastern transect, medium-grained sand predominates and has ripples similar to those seen on the western dive. The ripples seem recent, as they are crisscrossed by only a few tracks and trails of organisms. In several places gravelly material underlies the sand. Small sharp

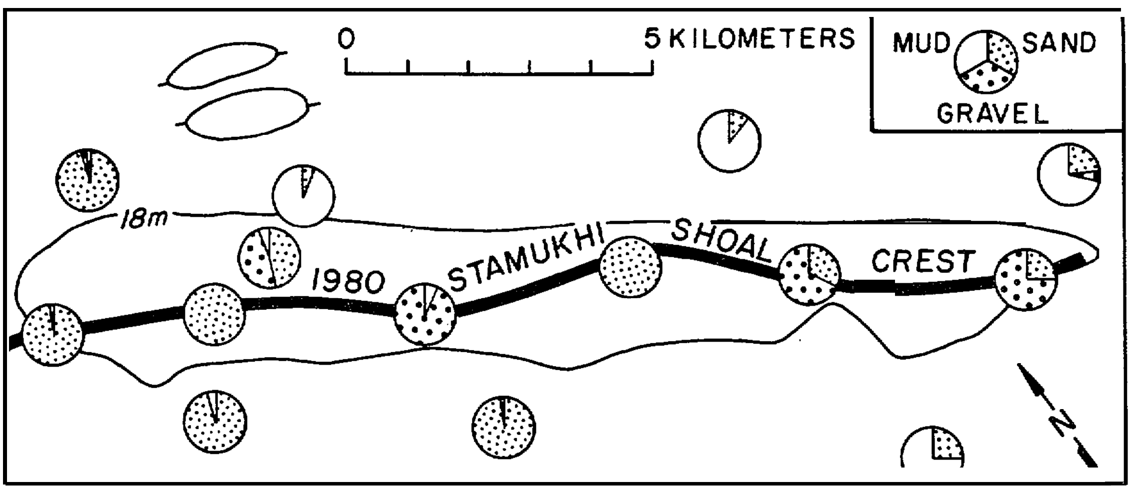


Figure 10. Sediment sample stations with pie diagrams showing the percentages of mud, sand, and gravel in relationship to the shoal crest in 1380. A **tongue** *of sand off the west end of the shoal extends seaward and includes the two small shoals shown. Mapped area matches Figs. 2, 7, and 8, and is keyed to Fig. 1.*

ledges underlain by mud layers occur in some gouge flanks. A few snails, small clams, coelenterates, and pectens were seen, but there were no attached organisms.

F. 1977, 1980, and 1981 Bedform Comparison

Lack of precise navigation in 1980 precludes direct comparison of monographs from 1977 and 1980. The patterns observed in both years, however, are consistent and show that the fairly heavily gouged crestal region of 1977 was replaced by ripple fields, which have crests spaced about 1.5 m apart and oriented at 150°, in 1980. In other regions of the shoal, gouge patterns in those two years show no noticeable difference.

Three of the 1977 bathymetric profiles (B, C, and D of Fig. 2) were rerun in 1981 for a comparison (Fig. 11). Although the vessel cannot be steered precisely enough to duplicate traverses exactly, major changes in gouge pattern are evident. In particular, numerous newly cut large gouges in the 1981 records did not exist in 1977. Large-scale changes in profiles B and C

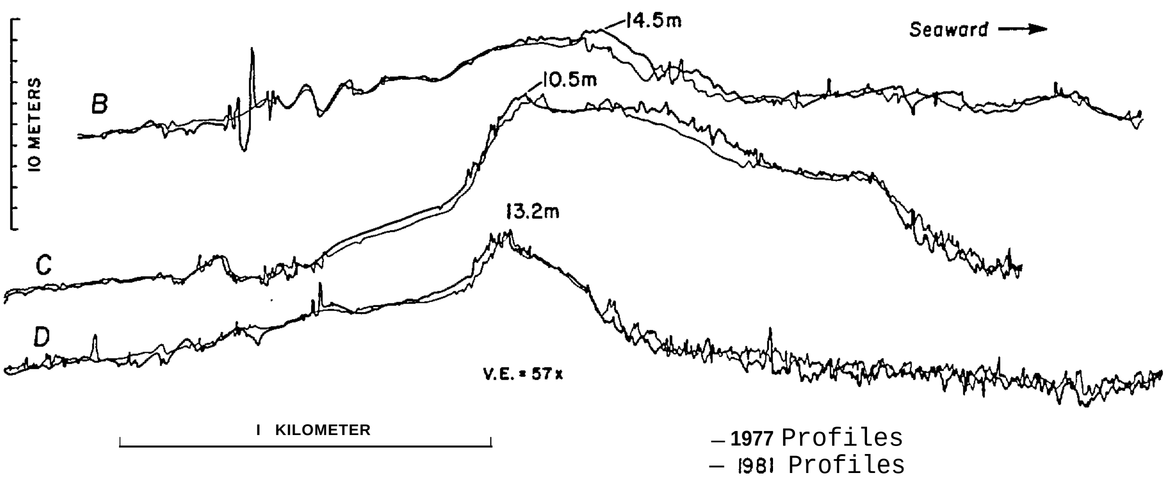


Figure 11. Comparison of profiles B, C, and D (Fig. 2) in 1977 and 1981. The 1981 cross section lines deviate horizontally up to 10 m from the 1977 lines and cross the dominant gouge trend at an oblique angle, so it is impossible to match individual gouges. However, this comparison does show that major changes have occurred on the shoal.

evidently also occurred, but further monitoring is required before any discussion of these is possible. Additional changes observed between 1980 and 1981 are the disappearance of ripples in the crestal region and the apparent development of ripple fields, which have a similar wavelength and orientation, on the seaward flank in the transition zone between heavily gouged and lightly gouged terrain.

IV. DISCUSSION

Hartmann (1891) strongly emphasized the effects of drifting ice in grinding, leveling, and polishing the shelf surface and shoreline in polar regions. He summarized observations from numerous explorers and ship captains and pointed out that the continuous motion of extensive and heavy ice masses in arctic regions may prevent the formation of sandy shoals that other processes tend to create under local conditions in the marine environment. The dredging and leveling action of ice may even help to explain the characteristically wide, smooth, and very gently sloping arctic shelves, where water depths of only 10 to 15 m are not uncommon several tens of kilometers from shore and where there is very little relief over wide regions. However, Stamukhi Shoal and other arctic shoals are made predominantly of sand accumulated since the last transgression (Reimnitz and Maurer, 1978); this suggests that ice processes may actually contribute to the formation and maintenance of sandy shoals in certain areas.

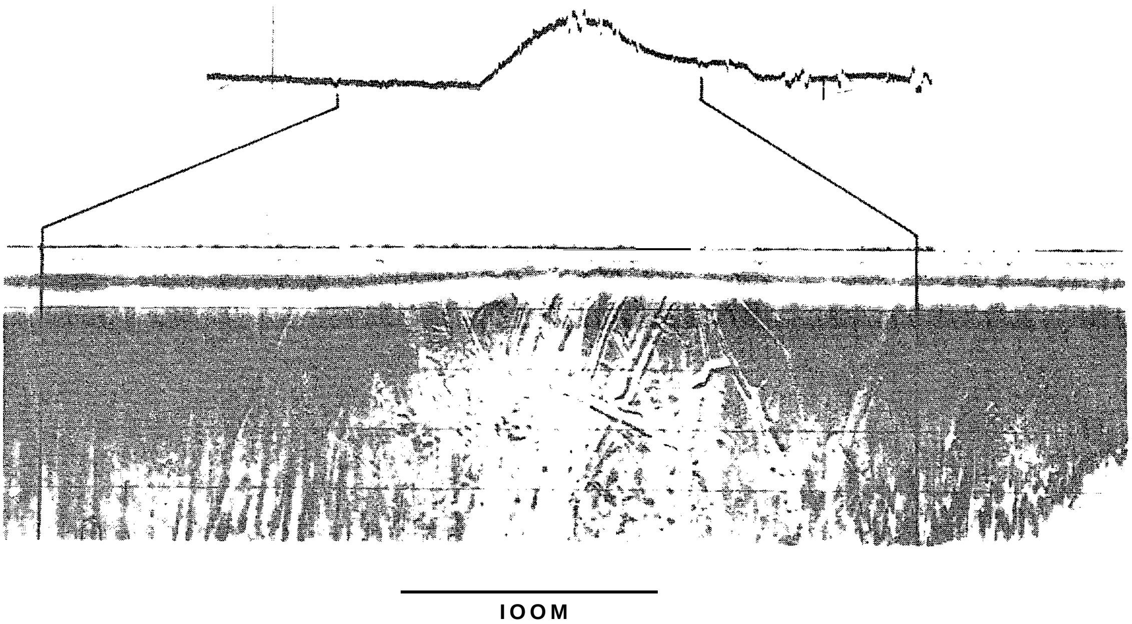
The satellite data presented here document both the interference that Stamukhi Shoal causes to drifting floes and ice islands and the deformation of extensive winter ice sheets focused on the shoal year after year. Stamukhi Shoal is able to resist the motion of tabular ice islands up to 200 m across (Brooks, 1973) and produces ice jams extending 100 km or more updrift. The precise matching of ice features seen in satellite images to the crest of the shoal indicates the scouring action of ice is most frequent and intense along the crest. Like a harrow dragged over a field of furrows, the keels of the drifting ice pack displace materials from the crests of shoals toward the sloping flanks. Here additional downslope movement of particles is aided by gravity. Only the scale of the processes on a farmer's field and the arctic shelf surface differs.

The ice drag marks on Stamukhi Shoal do not deviate from the regional trends in the years of record, indicating little topographic steering effect by the shoal. Ice either bulldozes across the shoal or plows into the side and stops. How have Stamukhi Shoal and other similar shoals survived?

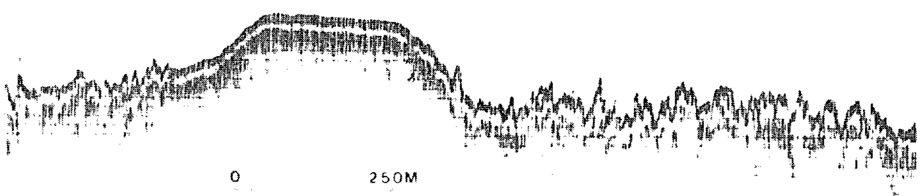
An interplay between ice scouring and hydraulic shaping of shoals must be considered to explain their maintenance. From 1970 through 1977 we were impressed by the intensity of scouring on the shoal crests in the Beaufort Sea compared to that on the low-lying surrounding terrain, as seen both in bottom observations and in the distribution of grounded ice (Reimnitz *et al.*, 1972, 1977, 1978b; Reimnitz and Barnes, 1974; Barnes and Reimnitz, 1977; Barnes *et al.*, 1978). A sample sonograph and fathogram recorded on Loon Shoal (Fig. 12A) in 1977 demonstrates the intensity of scouring. In contrast, Fig. 12B also shows a shoal profile representing the other extreme, a profile recently shaped by waves or currents. This example was recorded in 1981 over a sand shoal in the stamukhi zone 250 km east of the present study area. A similar smoothing of the crest of Stamukhi Shoal was documented from 1977 to 1980. The falls of 1977, 1978, and 1979 may well have provided the conditions for reworking the shoal by waves and currents: the fall of 1977 was marked by a shelf entirely clear of ice and resulting long fetches for wave generation, and the falls of 1978 and 1979 were marked by unusually strong northeasterly winds. The ripple patterns on top of Stamukhi Shoal, characterized by their long, continuous, slightly sinuous crests and their apparent symmetry, suggest orbital flow in a wave train as the most likely ripple generating process. The orientation of the ripples (150° to 170°) is aligned for easterly to northeasterly storm waves.

Using the most severe wave conditions on record, one may estimate the maximum particle sizes that could be moved on the crest of Stamukhi Shoal. Short (1973) recorded a 2- to 2.5-m-high swell with a 9- to 10-s period in early September 1972 inshore of Stamukhi Shoal. Following procedures outlined by Komar (1976), orbital velocities of up to 86 cm s^{-1} are estimated for these conditions at 15-m depths. This velocity is near the threshold of motion for particles of 7-mm diameter, or small pebbles. In September 1977, when most of the ice had disappeared from the shelf, we measured 2-m-high waves with a period of 6 s in water 15 m deep during a northeasterly wind of approximately 20 knots. Based on the above procedures, these waves could result in 40 cm s^{-1} orbital velocities, capable of moving medium-grained sand at a depth of 15 m. According to preliminary analysis, orbital velocities of about 100 cm s^{-1} (approximately 2 knots) could have produced the ripple fields of 1- to 1.5-m wavelength in gravel 20 mm in diameter.

Knowledge of the distribution and concentration of ice during major storms is required for wave hindcasting, but such information is essentially nonexistent for the periods during which the gravel ripples formed on Stamukhi Shoal. We therefore refrain from such analysis. However, two days of easterly winds having daily average velocities of 16 m s^{-1} (35 mph) and higher, recorded by the National Weather Service at Barter Island during a freeze-up storm in 1978, was an unusual event that produced large amounts of sediment-laden slush ice in the Beaufort Sea. We suspect that little drift ice was present to calm the seas and that the gouges on the crest of the shoal were transformed into ripple fields during the event.



A. pre-1977



B. post-1977

Figure 12. Comparison of a shoal reflecting the high scour intensity on the crest (typically seen prior to 1977) to another shoal typical of those seen in the years since 1977. (A) Sonograph and fathogram recorded on Loon Shoal [approximately 10 km southeast of Stamukhi Shoal) in 1977 contrast with (B) sonograph of a sand shoal in 1981 in the stamukhi zone 250 km east of study area. Both shoals rise approximately 4 meters above the surrounding seafloor.

The large sand waves that have steep faces to the east along the lower south flank of Stamukhi Shoal (Fig. 8) must have formed from continuous currents flowing toward the east. Differing orientations of other sand waves in the area suggest that strong currents may have been funneled and deflected by large grounded pressure ridges.

Stamukhi Shoal, a deposit of noncohesive sand and gravel, stands as an anomaly above the surrounding shelf surface that is covered with cohesive Holocene mud. On the basis of shallow seismic stratigraphy, Reimnitz and Maurer (1978) interpreted the shoal to be a Holocene constructional feature. They rejected the possibility that Stamukhi and other linear shoals in the area are drowned barrier islands and argued that shoals are built and maintained by modern ice-related processes from surrounding shelf deposits. Grounding ice, churning and softening bottom deposits and at the same time producing rough relief, makes materials readily available for removal by waves and currents, thereby aiding the winnowing of fine materials. The surrounding shelf deposits not only provide the range of coarse particle sizes that make up the shoal, but winnowing by the combined action of ice and currents in the vicinity also maintains the shoal as a coarse deposit.

Frequent ice scouring in a localized area, repeated over long time intervals, results in local coarsening of existing bottom deposits. However, we cannot envision an ice-related process that would result in slow and systematic construction of a major topographic high like Stamukhi Shoal. The repeated action of ice could only have the opposite result--that of leveling. We know of no evidence that a major topographic high in the Arctic was built by a single catastrophic event, and we believe that this is unlikely. Once a shoal is constructed to an elevation that exceeds the depth range through which grounded ice can be pushed upward on a steep slope in the natural environment, some ice would get stuck on the stoss side. Each event terminating on the stoss side would move material toward the crest. However, the amount of ice that continues to move over the shoal, instead of stopping on the stoss side and adding material to the shoal, is much larger and more efficient in lowering and reducing a shoal.

If the boundary of heavily gouged terrain on the stoss side of the shoal marks the area of long-term grounding after floes are shoved up the slope, we should see such characteristic signs such as increasing gouge size and terminal ridges. If, on the other hand, that boundary is controlled by the water depth to which wave reworking is active, it should show signs of sand patches inundating areas of ice-gouge relief along the crest of the shoal. The area mosaicked using total side-scan sonar coverage shows no signs of either process (Fig. 9). The boundary typically is a 300-m-wide mottled or pitted transition zone. We speculate that this characteristic bottom type may be the footprint of a pressure ridge formed in place, where relatively small ice slabs are shoved into the bottom and subsequently melt.

Pebbles provide an ideal base for biologic growth in certain ice-sheltered areas on the shelf. However, the continuously repeated grinding by ice and reworking by waves and currents makes Stamukhi Shoal a hostile environment for fauna and flora. Diving traverses reveal desert-like conditions where attached or burrowing organisms are almost totally absent. Iron-staining on all coarse clasts suggests frequent turnover of the clasts, so that all faces of pebbles are exposed to oxidizing conditions.

Stamukhi Shoal plays a key role in establishing the regional ice regime and provides considerable shelter locally against drifting floes and ice islands. It is the best known of the shoals that mark the edge of the stamukhi zone, but reconnaissance studies have been made on several other shoals. Weller Bank, marked by the large ice accumulations west of Stamukhi Shoal in the two summer satellite photos of Fig. 5, was compared by Barnes and Reiss (in press) to Jaws Mound, another shoal north of Prudhoe Bay. They reported that both shoals are elongated parallel to regional isobaths and consist of sand and iron-oxide-stained gravel, partly inundated by sand blankets on their east ends. In 1980 both of these shoals had only short irregular gouges on the crest, none on the flanks, and many large gouges seaward of the shoal. Ripples with wavelengths of 1.5 to 2 m, oriented at 130° to 150°, were also observed. These two shoals are, at least superficially, similar to Stamukhi Shoal, which indicates that it may serve as a model for all shoals in the stamukhi zone. However, there are also important differences. Stamukhi Shoal is the most linear shoal and has the greatest relief of any of the shoals yet studied in the stamukhi zone. Also, Stamukhi Shoal is more consistently marked by grounded ice than other shoals of the region. Until more studies of the entire stamukhi zone are made, it would be unwise to apply the findings of this study to all shoals in the zone.

The landward edge of the stamukhi zone east of the study area is marked for at least 150 km by a line of morphologic features much more subtle than Stamukhi Shoal (Rearic and Barnes, 1980; Barnes and Reiss, in press). This boundary generally follows the 18-m isobath and shows up as an anomaly in numerous ice-gouge parameters (Barnes *et al.*, this volume). For the first 35 km east of Stamukhi Shoal, the boundary is characterized by 3- to 4-m-high shoals that gradually decrease in size eastward to form a 2- to 4-m-high bench that has a sharp seaward edge (Barnes and Reimnitz, 1974; Reimnitz and Barnes, 1974; Barnes et *al.*, 1980; Rearic and Barnes, 1980). Very small shoals are present along the sharp seaward edge of the bench in some areas, perhaps marking the initial stages of major future shoals. Eastward of longitude 146° W, the boundary is again marked by subtle shoals (Rearic and Barnes, 1980).

Soviet navigators apparently have long taken advantage of large grounded ice piles present in the stamukhi zone of the East Siberian Sea, as reported in H.O. Publication No. 705 (1957): "In summer ice-free water is found between the stamukhi and the coast, providing a fine shelter for ships from the drift ice still present in the northern part of the sea. This area also may be used as an anchorage by a ship forced to winter over." In the Alaskan Beaufort Sea, petroleum development could also use the presence of shoals in the stamukhi zone to advantage (Reimnitz *et al.*, 1978a). The shoals may become sites for artificial islands used for exploration and production because the shallower seafloor would greatly reduce construction costs. We need, however, a better understanding of how ice interacts with these shoals, especially in the fall when the ice is thin. Conditions on the shoal, which is a focal point for ice dynamics, must be considered extremely hazardous. Lastly, the sand and gravel that compose Stamukhi Shoal are valuable as construction materials, and mining the shoal will be considered. But removal of the shoal could change the ice regime over wide regions of the shelf to the west and southwest and thus should be avoided.

IV. SUMMARY

Since the first Landsat images were taken in 1972, anomalies in the ice cover observed in the study area have suggested the presence of an uncharted topographic feature. A bathymetric survey over the area in 1977 revealed Stamukhi Shoal, a 17-km-long linear shoal with up to 10 m relief. In eight out of ten summers, satellite images have shown at least one of four characteristic ice features coinciding with the shoal: (a) sharp boundary separating open inner shelf waters from dense pack ice offshore, (b) the edge of a major lead, (c) an isolated belt of stamukhi, and (d) an isolated belt of grounded ice islands. A lack of imagery is probably the reason no characteristic ice pattern was recorded in two summers. In all ten winters of satellite data, the shoal has coincided with at least one of three characteristic ice features: (e) major pressure and shear ridges, (f) a boundary between extensive fields of different ice types, and (g) an indistinct line of ice piles.

All of the observed ice patterns require grounding on the crest of the shoal. The shoal has no apparent topographic steering effect on pack ice; thus a large amount of energy is consumed there by ice scouring. Before 1977, the crests of Stamukhi Shoal and other shoals in the grounded-ridge zone were marked by high numbers of ice gouges. In recent years, active hydraulic reworking of material on the crests of the shoals has smoothed the gouges, and left wave-generated ripples in gravel patches. Physical disruption of the shoals by ice keels alternating with scouring by currents results in removal of fine materials and concentration of coarse materials in the shoal. Stamukhi Shoal is thus maintained against an energy gradient of presumably destructive forces that are focused on the crest. On the other hand, the shoal is a constructive feature postdating tie last transgression. This dichotomy exposes a major gap in our understanding of processes on the shoal. Because shoals of the stamukhi zone may play roles in the offshore petroleum developments, further research is highly desirable.

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